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by C. G. Fountzoulas, P. G. Dehmer, J. M. Sands, and J. H. Yu

ARL-RP-251 **June 2009**

A reprint from the *Proceedings of the 24th International Symposium on Ballistics*, Vol. 1, pp. 481–488, New Orleans, LA, 22–26 September 2008.

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ABSTRACT

Recent advances in the numerical techniques, higher computing power and materials model have allowed the accurate simulation of the ballistic impact into monolithic and multi-layer transparent armor configurations. In the current effort, the velocity profile during the ballistic impact of 0.22-cal and 0.15-cal fragment simulating projectiles (FSP) into a polymethylmethacrylate (PMMA) target, which was a Plexiglas G manufactured by Atofina Chemicals was simulated using the ANSYS/AUTODYN commercial software. Our successful previous modification of the existing PMMA material model [1] resulted in accurate prediction of experimentally produced cracks and the V50 impact velocity for all cases. The energy dissipation through a monolithic and laminated acrylic target impacted by the above mentioned FSPs was studied by analyzing the simulated velocity profile of each projectile, an important design parameter. The purpose of this report is to study these profiles and to produce their analytical expressions, by using standard numerical regression techniques.

INTRODUCTION

The dominant materials solution used for ballistic transparency protection of armored tactical platforms in commercial and military applications is low cost glass backed by polycarbonate. Development of next generation ceramics and plastics is critical to offering enhanced protection capability and extended service performance for future armored windows to the soldier. Light armor was initially studied by M: L. Wilkins C. **A.** et al [2]. Quoting from another study, also by M.L. Wilkins et al [3], they report that “The important projectile parameters for target penetration are geometry, material strength, density, and velocity. For this discussion geometry refers to the sharp point used in the design of armor piercing projectiles. Material strength is the parameter that permits the projectile to maintain the designed armor-piercing shape during the penetration process. The projectile material strength is important until a target that is stronger than the projectile is encountered. Then, the penetration process is governed by the projectile mass and velocity. For example, ball and armor piercing, and projectiles with the same mass have about the same ballistic limit for ceramic targets strong enough to destroy the tip of the armor piercing projectile.”

The U.S. Army has invested heavily in the development of next generation materials, including ceramics, for military systems [4]. The result of the on-going investments is a critical understanding of various candidate materials strengths and weaknesses for military platforms.

Finite element modeling has progressed substantially in the ability to predict failure of materials under extreme dynamic loading conditions. One of the limitations of predictive models is lack of a complete dynamic materials properties database which is needed for materials models for each of the materials in the simulations. In order to compensate for parameters whose dynamic values were extrapolated from their static or quasi-static properties, baseline experiments are often used to recalibrate the models [5, 6]. Finite element tools can be applied effectively to reduce the variability between impact tests and can be used to validate designs with fewer experimental failures, when robust models are created [7].

The objective of this effort is to study the energy dissipation through acrylic targets of varying thickness and architecture impacted by various size FSPs and to produce analytical expressions of the velocity profiles by using regression analysis tools.

EXPERIMENTAL

Ballistic measurements were carried out at using a 17-gr, .22-cal, and a 5.85-gr .15 FSP, which were launched from a compressed helium gas launcher The cross-section area of all the acrylic targets was 152.4-mm x 152.4-mm. Monolithic targets of thickness 11.82-mm and 5.92-mm were impacted by .22-cal and .15-cal FSP respectively at various impact velocities, to determine the V50. A third target, which was consisted of two 5.92-mm thick plates of acrylic without any adhesive between them-total thickness of the set 11.84-mm- was impacted by a .22-cal FSP. All targets were sandwiched in a transparent frame. All shots were conducted with the target normal to the projectile line of flight, i.e., 0° obliquity.

A high-speed camera (Phantom v7, Vision Research), aiming at 90^o to the path of the FSP, was used to record the impact on the plates (Figure 1). The targeting area was illuminated by backlighting using a high intensity halogen lamp and a diffuser was used to spread out the light intensity. The focal length of the lens was 70 mm.

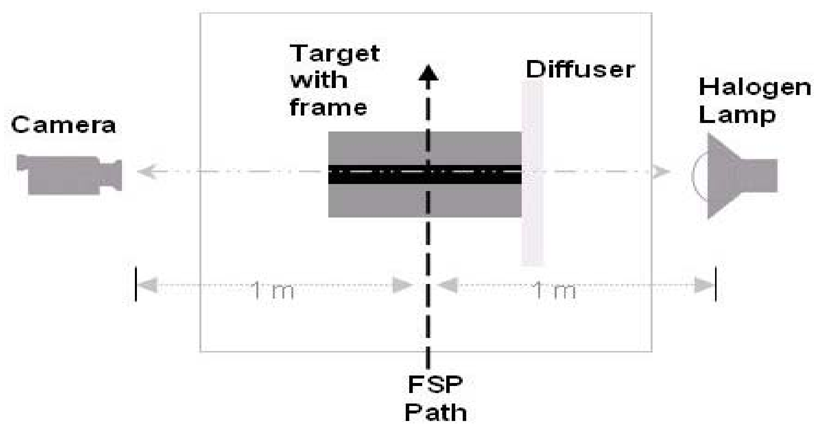


Figure 1. High-speed camera setup

The f-stop was set to f/8 to increase the depth of field. The exposure time was 2 μs at 25,000 frames-per-second, and the resolution was 512 × 256 pixels. Phantom Cine motion analysis software was used to calculate the impact speed and the residual speed of the FSP.

MODELING

One of the advantages of modeling methods is the ability to create physically challenging architectures and to investigate ballistic effects otherwise impossible or extremely difficult, expensive and time consuming to study experimentally. The sensitivity of ballistic measurement tools is typically less than ±10% due to the range of available failure modes invoked in the high energy exchange between projectile and target. Additionally, capturing the real-time failure modes in the impact event requires highly specialized video equipments. These factors contribute to a very difficult and expensive set of experiments for investigating small flaws and the impact on performance in the experimental realm.

The 3-D modeling targets were consisted of identical to the actual target geometries and architecture, as they are described above, and were impacted by .22 and .15 FSP models of identical to the actual FSP geometry. The ballistic behavior of the impact was studied by simulating the impact process by using the non-linear ANSYS/AUTODYN commercial package [8]. The modified material models of acrylic, which has been added to our AUTODYN library, and the steel material models were obtained from the AUTODYN library. The simulation was carried out using three-dimensional axisymmetric models and smooth particle hydrodymamics (SPH) solver. The particle size used for SPH solver was 0.5-mm. Results were obtained by simulating projectiles impacting the targets at the experimental V50 velocities of 350 m/s for the 11.84-mm thick targets and 210 m/s for the 5.92-mm thick target, respectively.

(a) (b)

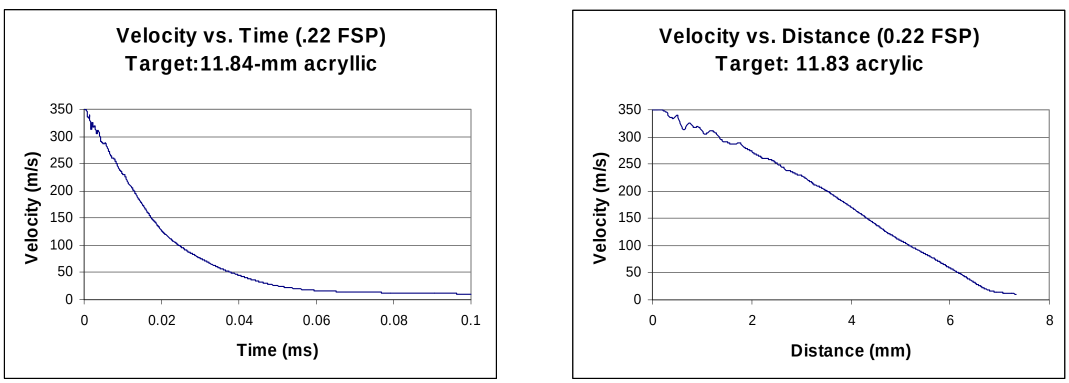
Figure 2. (a) Actual impact; (b) simulated impact. Actual and simulated target were impacted by .22-cal FSP at 350 m/s.

All simulated exit velocities were within a few meters from the experimental V50 velocities, without any further calibration of the used models required. Figures 2a and 2b show a photo of an actual 11.84-mm thick acrylic target impacted by a .22 FSP at 350 m/s and a photo of the simulation of an identical target also impacted by a .22 FSP at 350 m/s respectively.

It is worth noting the similarity between the actual and the simulated photos, which in addition to the prediction of the exit velocity (V50) validates our simulation results further.

ANALYTICAL STUDY AND DISCUSSION OF RESULTS

The main objective of this effort was to determine and analytical expression of the velocity profile of FSP projectiles as they travel through an acrylic target after the impact. Figures 3a and 3b show the simulated velocity profile vs. time and vs. distance respectively of a 0.22-cal FSP travelling through a 11.84-mm thick acrylic target. All our impact simulations produced similar velocity profiles.



(a) (b)

Figure 3. Velocity simulated profiles vs. (a) time; and (b) vs. distance travelled through the target.

To determine the analytical expression of the profiles of all impacts the LINEST statistical function of the Microsoft Excel was used. This function calculates the statistics for a line by using the "least squares" method to determine a straight line that best fits your data, and then returns an array that describes the line. This function, when compared to the LOGEST statistical function of the Microsoft Excel, which calculates an exponential curve that fits the data and returns an array of values that describes the curve, it resulted in more accurate representation of the simulated velocity profiles.

Figures 4-6 show the results of the regression analysis of all the simulated impacts. At these curves the normalized velocity with respect to the maximum impact velocity is plotted against the normalized distance with respect to the maximum distance of the FSP travelled through the acrylic target. As it is can be seen in these curves the fitting reproduced the velocity profile accurately.

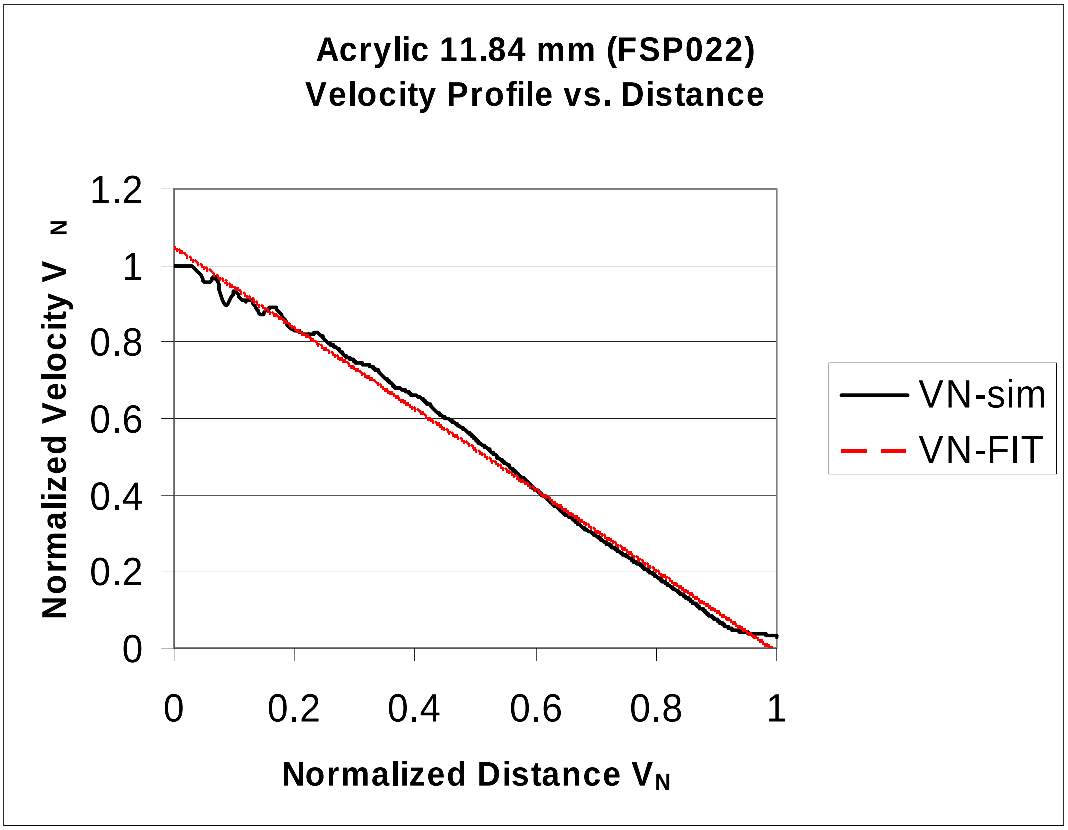


Figure 4. Simulated vs. fitted profiles of a 0.22 FSP travelling through a 11.84-mm thick acrylic target.

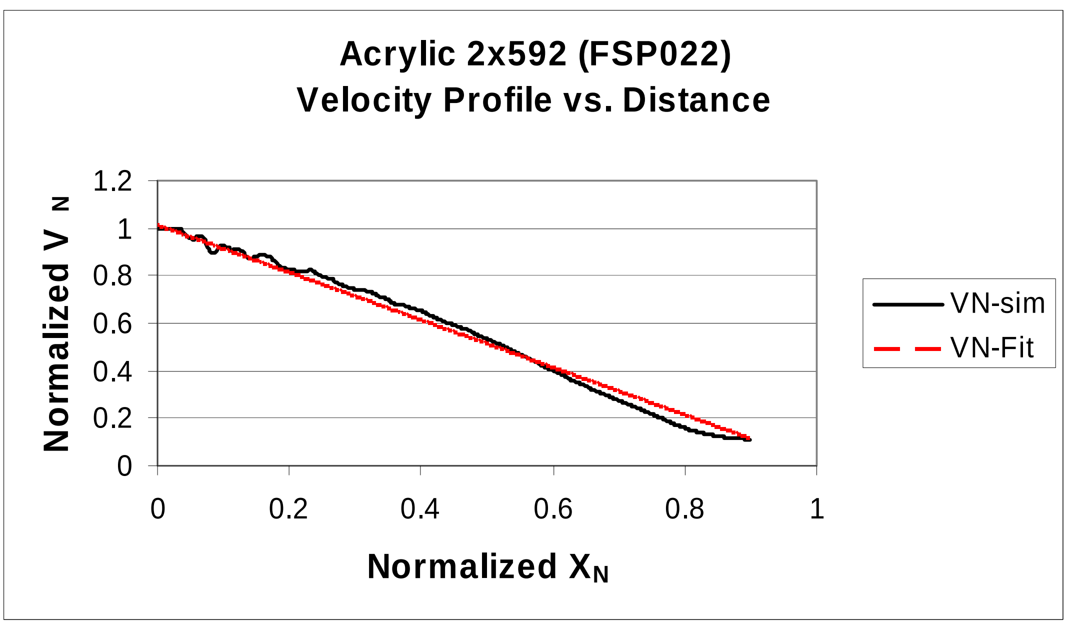


Figure 5. Simulated vs. fitted profiles of a 0.22 FSP travelling through a 2x5.92-mm thick acrylic target.

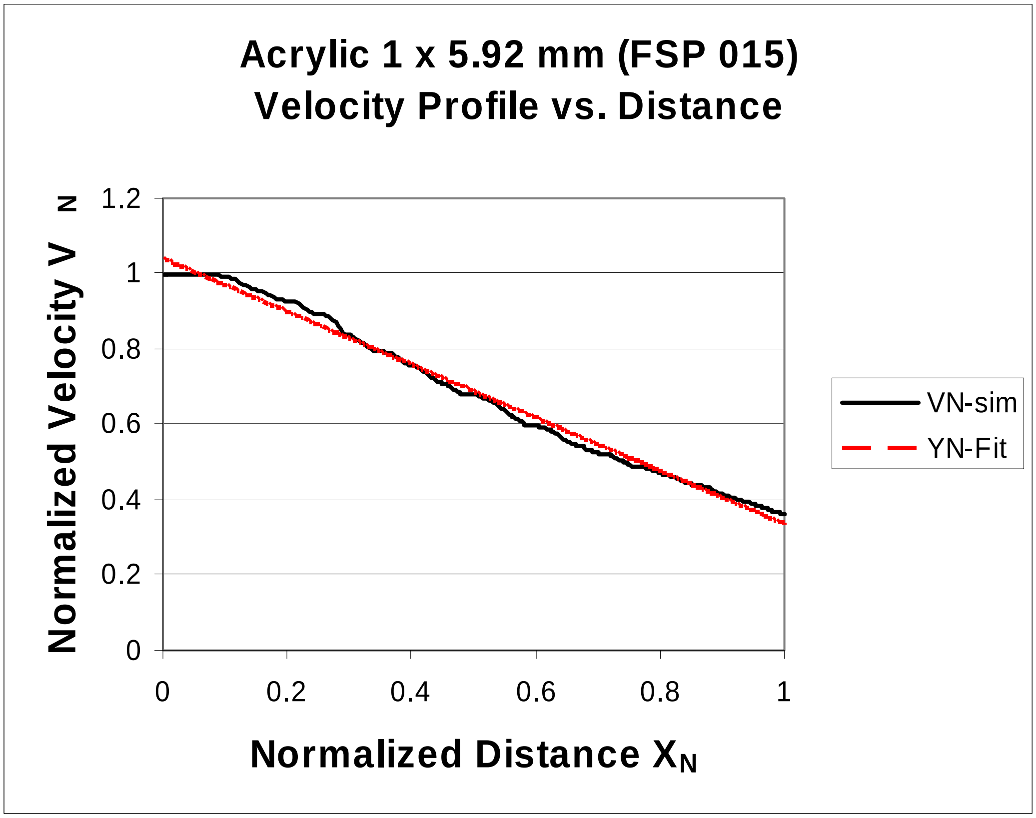


Figure 6. Simulated vs. fitted profiles of a 0.15 FSP travelling through a 5.92-mm thick acrylic target.

TABLE I shows the equations of the best-fit curves for all the studied cases.

TABLE I. EQUATIONS OF THE BEST-FIT CURVE OF ALL SIMULATED IMPACTS

Target	Projectile	Velocity	Equation
1x11.84-mm	.22-cal FSP	350 m/s	$V/V_{MAX} = 1.046 - 1.056X_N$
2x5.92-mm	.22-cal FSP	350 m/s	$V/V_{MAX} = 1.010 - 0.888X_N$
1x5.92-mm	.15-cal FSP	210 m/s	$V/V_{MAX} = 1.039 - 0.7045X_N$

The produced equations indicate that the slope of the velocity profile, which in turn indicates the energy loss per unit thickness travelled, decreases with increasing FSP size (increasing mass) and target architecture (Figure 7). It also is observed that lamination of the target affects the slope of the velocity profile, which in turn verifies the adopted practice of target lamination for more efficient impact energy absorption by target of same areal density design but of different architecture. Although the V50 of the 11.84-mm and two-5.92-mm thick acrylic targets are very close, their equations indicate that the energy dissipation through these targets is clearly affected by their architecture.

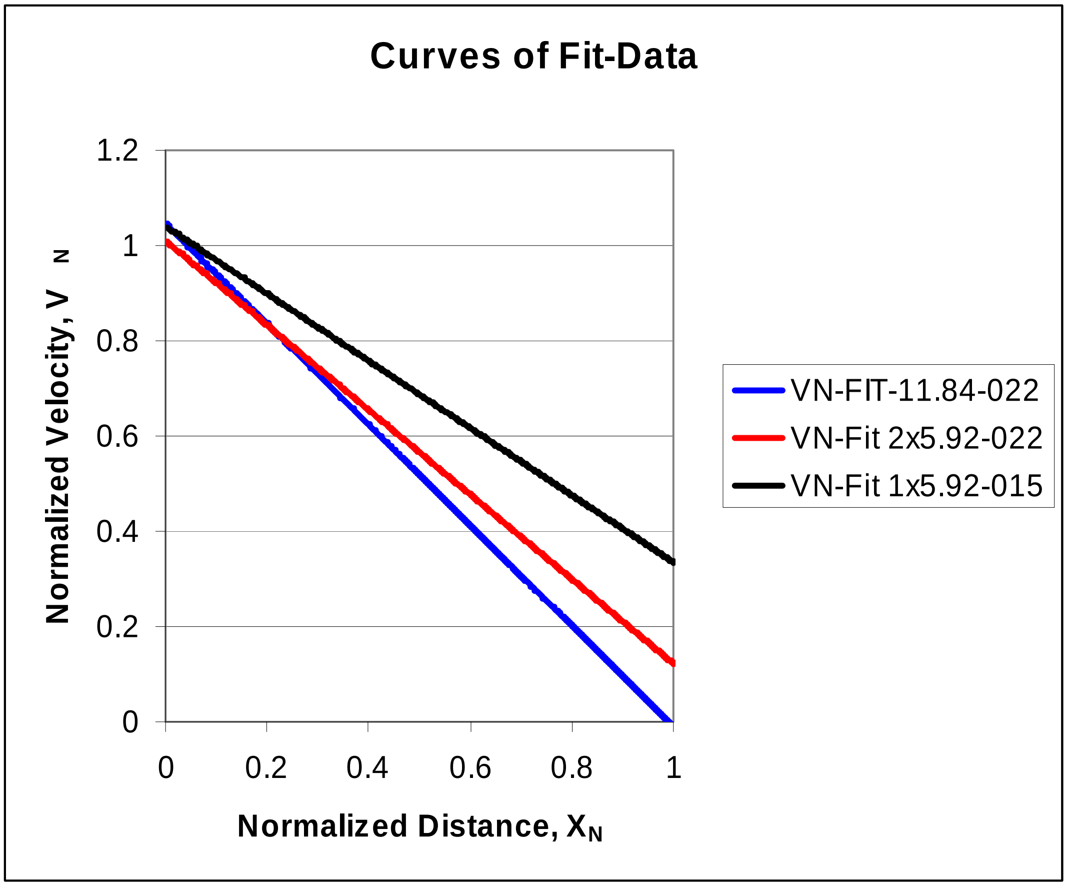


Figure 7. Summary of all curves of fit-data.

CONCLUSIONS

While the need for advanced materials solutions for protection of vehicles from ballistic threats continues to grow, the ability to predict materials performances using advanced modeling tools increases. The current paper has demonstrated the powerful use of computational modeling to produce analytical expressions for the prediction of the energy absorption by an acrylic target, which is impacted by various size FSPs. The results of the current study indicate, the already known experimentally, that the resistance of an acrylic target to impact by FSP projectiles is affected by the size of the FSP, impact velocity and target architecture. The decreasing slope of the produced analytical expression quantizes those findings. The use of existing statistical software in Microsoft Excel resulted in fast but successful analytical expressions. Currently, there is an effort to further study and delineate these equations towards a generalized energy absorption equation by an acrylic target impacted by an FSP, as a function of the FSP size, impact velocity and target areal density towards a more effective design.

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